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LASA Decision Probabilities
for $M_S - m_b$
and Modified Spectral Ratio

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AND MODIFIED SPECTRAL RATIO

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Group 22

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ABSTRACT

LASA data has been analyzed to determine the probabilities that $M_S - m_b$ and Modified Spectral Ratio (MSR) can be effectively applied to seismic events. The probabilities have been estimated as a function of magnitude and whether the event is an explosion or an earthquake. In the case of the earthquakes, the probabilities go from about 1.0 to 0.0 as m_b goes from 5.0 to 4.0. The drop is slightly faster for $M_S - m_b$. MSR behaves similarly for explosions. However, the probability for $M_S - m_b$ in the case of explosions drops to zero roughly over the range of m_b from 5.2 to 4.5. In addition, a limited study of joint properties of $M_S - m_b$ and MSR has indicated that they operate quite independently in the sense that if one of the discriminants yields no decision concerning a particular event, the probability that the other can make a decision is not significantly affected.

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LASA DECISION PROBABILITIES FOR $M_S - m_b$ AND MODIFIED SPECTRAL RATIO

I. Introduction

It is now generally recognized that if an underground nuclear explosion and a normal depth earthquake radiate equal amounts of energy as short period compressional body phases then the earthquake will normally generate significantly more long period surface wave energy than the explosion. One crude measure of the surface wave energy is the surface wave magnitude, M_S . The body wave magnitude, m_b , is a measure of energy in the compressional body phases (1), (2). If M_S is plotted against m_b for a set of explosions and earthquakes, the points tend to separate into two groups. A new event can be identified as an explosion or earthquake by noting where it is located in the M_S, m_b plane. This is the $M_S - m_b$ method for discrimination. A number of researchers have reported upon the efficacy of this discriminant (3), (4), (5), (6), (7), (8).

Most studies of $M_S - m_b$ have emphasized its value as a discriminant when both M_S and m_b can be measured. It is also important to determine the probabilities that the appropriate measurements can in fact be made. In particular, if an m_b measurement can be made at LASA, what is the probability that the $M_S - m_b$ criterion can be applied using LASA data only? The probability will depend upon the m_b value and true nature of the event. Some estimates of such probabilities have been obtained for LASA and are presented in the sequel.

Another discriminant of particular value which uses LASA data is spectral

ratio (9), (10). One basic form of this discriminant makes use of the ratio

$$\rho = \frac{\int_{1.45}^{1.95} |X(f)| df}{\int_{0.35}^{0.85} |X(f)| df}$$

where $X(f)$ is the Fourier transform of 10 seconds of short period data which starts just before the onset of the P phase. If ρ is plotted against m_b for explosions and earthquakes the points for the two populations tend to separate. However, it is clear that ρ can be significantly affected by background noise. For this reason, Lacoss (8) introduced a modification to this basic spectral ratio test. The modification essentially consists of making no decision on events which have insufficient signal to noise ratio in the two frequency bands used to compute ρ . The modification effectively eliminates the possibility of erroneous classification of events on the basis of noise rather than signal.

The modified spectral ratio shares an important property with the $M_S - m_b$ criterion. If no surface waves are visible on long period seismograms, one does not blindly measure noise and thus attribute a false M_S value to an event. In a similar way, the modified spectral ratio (MSR) prevents one from blindly measuring ρ for noise dominated events. Thus, as is the case for $M_S - m_b$, there is a

probability that MSR can be applied. Such probabilities have now been estimated for MSR.

Given any set of events to be classified, there is one subset, C_0 , to which $M_S - m_b$ cannot be applied and another subset, C_1 , for which MSR indicates that no decision should be made. It is clearly of interest to know the extent of the intersection of these two sets. Some data of this type have been gathered and are discussed in this report.

The data base for this report is the same as that used previously by Lacoss (8). The explosion population consists of 35 Soviet, French, and American presumed or known underground tests recorded teleseismically at LASA. The earthquake population consists primarily of about 150 events with epicenters in the Sino-Soviet Bloc area. The material in this report is an extension of results previously presented by Lacoss (8).

II. Probability that $M_S - m_b$ and MSR Can Be Applied to Earthquakes

In this and all other sections only events with detected short period body phases have been considered. Figure 1 shows $M_S - m_b$ data for such a set of events. A possible decision line, which we consider to extend linearly outside the range of the figure, has been drawn on the figure. The implied decision rule is to decide explosion if an event plots below the decision line. Note that this decision does not require that a surface wave be recorded for the event. If M_S can be measured and the event is above the decision line, then the earthquake decision is made. However, if noise or other events obscure an event and it cannot be constrained to be in the explosion region, no decision can be made. Using the above decision rule, only one earthquake in our population would be erroneously identified as an explosion. The probability that no surface waves will be recorded for an earthquake and that the noise or an interfering event can bound the event in the explosion region appears to be negligible. Thus the probability that $M_S - m_b$ can be applied to an earthquake is the same as the probability that surface waves can be detected.

Figure 2 shows the basic data used to estimate the probability, $P_Q(m_b)$, that $M_S - m_b$ can be applied to an earthquake. $P_Q(m_b)$ is the product of $P_{NQ}(m_b)$, the probability that M_S can be measured when there is microseismic noise but no interfering event, and $P_{IQ}(m_b)$, the probability that no interfering event will obscure the measurement of M_S . It is these component probabilities, $P_{NQ}(m_b)$ and $P_{IQ}(m_b)$,

which can be directly estimated using the Figure 2 incremental histograms. $P_{NQ}(m_b)$ is estimated using the top two histograms. $P_{IQ}(M)$ is estimated using the top and bottom histograms. Figures 3 and 4 show the estimates of $P_{NQ}(m_b)$ and $P_{IQ}(m_b)$. All events located deeper than 100 km by USCGS were excluded when obtaining estimates.

Figure 5a shows spectral ratio for all events in the data base, except those reported deeper than 100 km by USCGS. Figure 5b shows spectral ratio for only those events for which MSR allows a decision. These two figures display the data available to estimate the probability that a decision can be made using MSR. In no case did an interfering event destroy the value of spectral ratio. Figure 3 shows the estimated probability $P'_{NQ}(m_b)$, that MSR admits a decision given that an event is an earthquake, and no other event is interfering with the short period data.

Estimates of both $P_{NQ}(m_b)$ and $P'_{NQ}(m_b)$ have been shown on Figure 3. There is no basic reason why, for a given m_b , these probabilities should equal each other. Nevertheless it is clear that within the bounds of experimental error, we can, in fact, assume they are equal. A nominal curve which can be used for either has been indicated on the figure. The nominal curve is the integral of a normal distribution with mean 4.35 and standard deviation 0.35. This curve is not optimal or best in any sense except that, subjectively, it appears to be a good fit to the data. This normal curve will henceforth be used for $P_{NQ}(m_b)$ and $P'_{NQ}(m_b)$.

Several possible nominal curves for $P_{IQ}(m_b)$ have been drawn on Figure 4. The scatter of experimental data is quite large. For this reason the choice of nominal $P_{IQ}(m_b)$ requires somewhat more comment than did that for $P_{NQ}(m_b)$ or $P'_{NQ}(m_b)$.

It has been often noted (11) that on the average for any fixed time interval, the number of earthquakes occurring throughout the world at above some magnitude m_b tends to be given by $A10^{-Bm_b}$, where B is a positive parameter on the order of unity. It is this observation and the assumption that earthquakes occur independently according to a Poisson distribution (12) which has suggested the form of $P_{IQ}(m_b)$ used here. If $\lambda(m_b)$ is the average number of earthquakes during a time interval T having magnitudes at least as large as m_b then $1 - e^{-\lambda(m_b)}$ is the probability that at least one such event will occur during time T . The several curves on Figure 4 are plots of this probability with $\lambda(m_b) = A10^{-Bm_b}$. The large deviation of experimental points for large magnitudes is most likely a peculiarity of our very limited data base.

All the curves on Figure 4 have been adjusted for an average of either 0.04 or 0.08 events having $m_b \geq 5.0$ during an interval T . If T is 15 minutes this is the same as 3.8 and 7.6 such events per day. For $T = 30$ minutes this is the same as 1.9 and 3.8 per day. These values are consistent with the number of such events reported daily by the USCGS. Curves have been shown for $B = 1.0$ and $B = 1.5$. These are typical B values one might find cited in the literature. The value $B = 1.5$ is more consistent with the original work of Gutenberg (11).

Figure 6 is a summary of the decision probabilities for $M_S - m_b$ and for MSR. In the case of spectral ratio the figure has been drawn showing a very minor effect of interfering events. The small probability of interference was arbitrarily assigned but is not inconsistent with observations. The relatively small probability of interference for MSR is due at least in part to the short time which must be free of interfering events. For MSR this time is usually a few tens of seconds. For $M_S - m_b$, the time may be 15-30 minutes. The effect of interfering events in the case of $M_S - m_b$ has been shown for the case $A = 1.26 \times 10^6$ and $B = 1.5$. When the effect of interfering events is taken into consideration we note that the probability of applicability of $M_S - m_b$ to earthquakes at a given m_b level is the same as that of MSR for an m_b value 0.1 to 0.2 magnitude units smaller.

III. Probability that $M_S - m_b$ and MSR Can Be Applied to Explosions

Let $P'_E(m_b)$ be the probability that MSR will generate a decision for an underground nuclear explosion with body wave magnitude m_b . All of the limited data available to estimate $P'_E(m_b)$ is contained in Figures 5A and 5B. $P'_E(m_b)$ has been estimated as follows. The number of explosions on Figures 5A and 5B in intervals $m_b \pm 0.4$ was determined for m_b at multiples of 0.1 magnitude units. Then $P'_E(m_b)$ was estimated as the ratio of these numbers. Such estimates are shown as the solid points on Figure 7.

Let $P_E(m_b)$ be the probability that $M_S - m_b$ will generate a decision for an explosion of magnitude m_b . Figure 1 contains part of the data needed to estimate $P_E(m_b)$. That figure shows all explosions in our data base for which $M_S - m_b$ generated a decision. In addition, there were seven explosions for which long period digital data were available but which could not be identified at LASA. The LASA body wave magnitudes of these events were 5.28, 4.95, 4.90, 4.69, 4.59, 4.40 and 3.86. The three unidentified events with magnitudes 5.28, 4.59, and 4.40 were the only explosions obscured by interfering events. Using this data $P_E(m_b)$ has been estimated as the fraction of all explosions in the interval $m_b \pm 0.4$ which appear on Figure 1. This estimate has been evaluated at each tenth of a magnitude and is shown as open dots on Figure 7.

A considerably more indirect way to estimate $P_E(m_b)$ has also been employed.

First consider only explosions without interfering events and for which the surface waves are obscured by LP microseismic noise. The value of decision probability for this set of events can be determined from a study of noise with no events present. The M_S bounds imposed by noise have been measured for a distribution of hypothetical epicenters in the Sino-Soviet Bloc using more than 40 noise samples. Figure 8 is a cumulative histogram of these bounds. Using this and the decision line on Figure 1 we have calculated the probability $P_1(m_b)$ shown on Figure 9. $P_1(m_b)$ is just the probability that the M_S bound imposed by noise will locate an event in the explosion region. If the bound does not constrain the event to that region then no decision can be made. The probability, $P_2(m_b)$, that M_S can be measured given there is no interfering event is also shown on Figure 9. It was estimated using ratios of explosion counts in intervals $m_b \pm 0.4$. The smooth curve for $P_2(m_b)$ is the same as that shown on Figure 3 with μ increased from 4.35 to 5.45. This shift of 1.1 magnitude units results from the similar difference between the means of the earthquake and explosion populations shown on Figure 1. If the probability of interfering events is zero then $P_E(m_b) = P_2(m_b) + (1 - P_2(m_b)) P_1(m_b)$. This has been drawn onto Figure 7 as the indirect estimate of $P_E(m_b)$. It is very nearly equal to $P_1(m_b)$. The effect of considering interfering events would be to shift the indirect estimate slightly to the right in the same way that it shifted the probability for earthquakes as shown on Figure 6.

IV. Comparison of $M_S - m_b$ and MSR

Figures 6 and 7 summarize the principal quantitative results in this report. In one sense these figures indicate the relative value of the $M_S - m_b$ and MSR discriminants, using LASA data only, as a function of magnitude and event type. If an event is an earthquake of magnitude m_b it is clear from Figure 6 that it has a slightly higher a priori probability of being identified by MSR than by $M_S - m_b$. However, it is fair to say that the ability of MSR to operate at lower magnitudes than $M_S - m_b$ on earthquakes is slight and amounts to a shift of only 0.1 - 0.2 body wave magnitude units. Roughly, the probabilities in both cases drop from 1.0 to 0.0 as m_b goes from 5.0 to 4.0. The situation is considerably changed in the case of explosions. For example it is clear from Figure 7 that MSR can be as effective at $m_b \cong 4.5$ as $M_S - m_b$ can be at $m_b \cong 5.0$. At $m_b = 4.5$ MSR will identify 10% of the explosions. (Presumably no decision is made concerning the remaining explosions), whereas $M_S - m_b$ will identify virtually no explosions. The probability for MSR is similar for earthquakes and explosions but for $M_S - m_b$ it drops from 1.0 to 0.0 roughly as m_b goes from 5.2 to 4.5. The net impact of Figures 6 and 7 is that MSR can play a particularly important role in discrimination for events with m_b less than about 5.0.

Although many events identified by MSR are also identified by $M_S - m_b$ and vice versa the two criteria can be quite complementary. This is true for large as well as small magnitude events. Consider the four shallow earthquakes with $m_b \geq 4.9$

indicated on Figure 2 which could not be identified by $M_S - m_b$ due to interfering events. A check of these events has shown that these earthquakes were correctly identified by MSR. This is to be expected since the events are large and interference of LP surface waves will not generally effect the short period P wave signal to noise ratio. Thus MSR operates as successfully as if there had been no LP interference.

A similar situation holds for smaller magnitude events as well. That is, the inability to come to a decision using $M_S - m_b$ and MSR are quite independent. This has been checked using earthquakes with $m_b \leq 4.5$ which might have been identified using $M_S - m_b$. Figure 10 is a Venn diagram, with areas proportional to the number of events in the indicated sets, which shows the degree of independence of $M_S - m_b$ and MSR. Both $M_S - m_b$ and MSR identified 30% of the earthquakes considered. If the two criteria operate independently then we would expect 9% of the events to be identified by both on the average. In fact 15% were identified by both. Considering the small number of events involved this is a strong indication that both criteria operate independently at these small magnitudes. This independence is anticipated if it is assumed that LP and SP interference by noise and signals is independent and that decisions are withheld whenever noise levels become too high.

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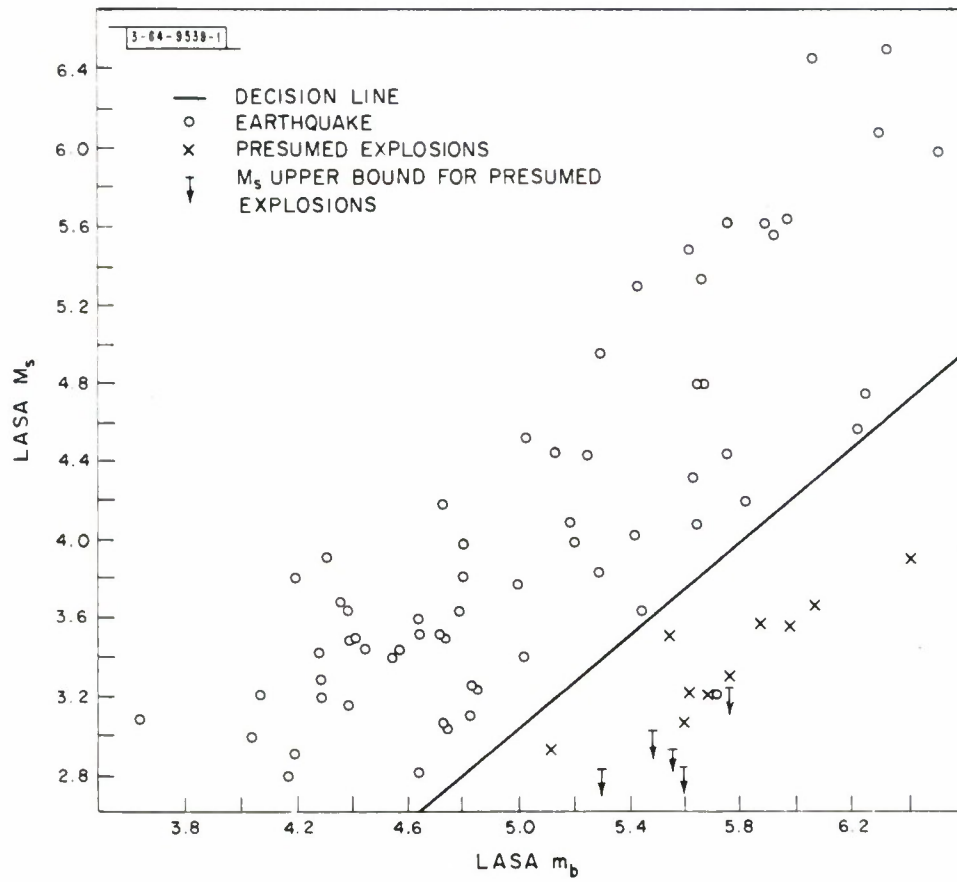
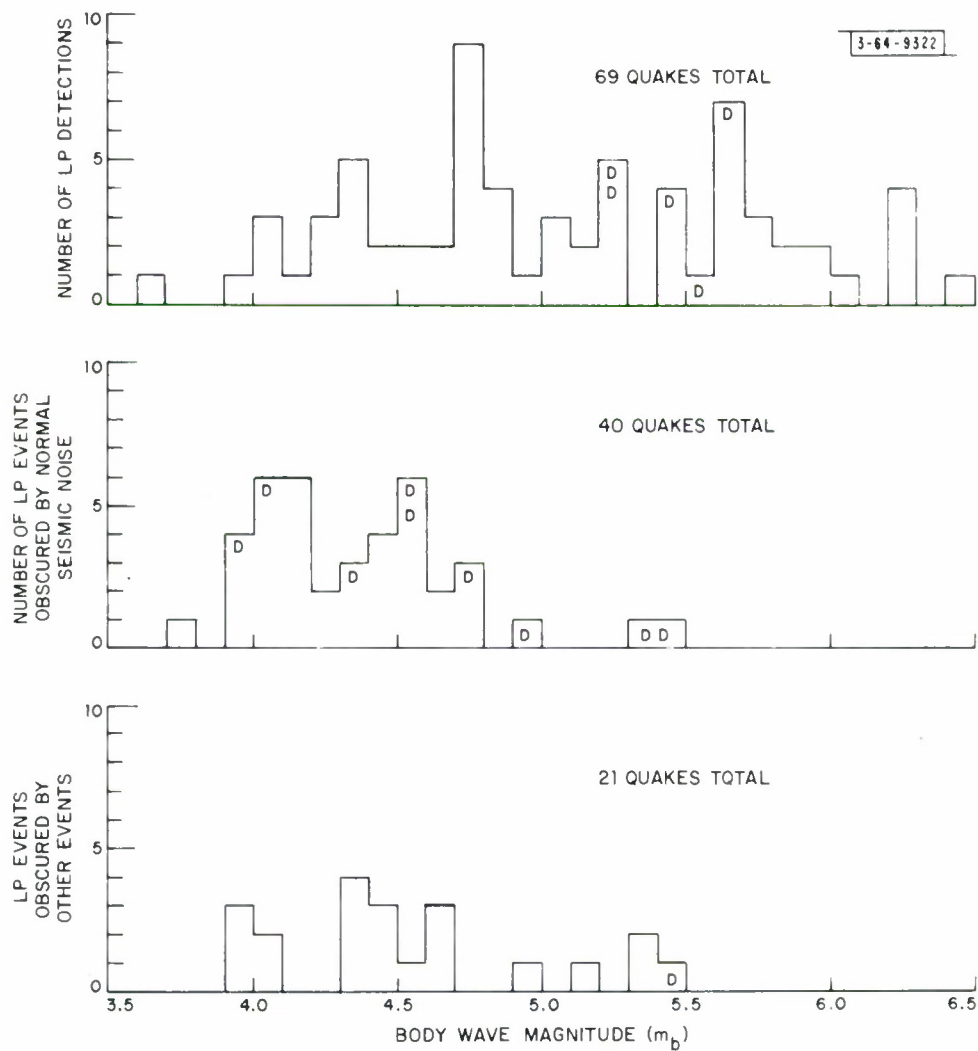


Fig. 1. $M_S - m_b$ discrimination.



NOTE: D INDICATES DEPTH GREATER THAN 100 KM

Fig. 2. Surface wave detection data for Sino-Soviet earthquakes recorded at LASA.

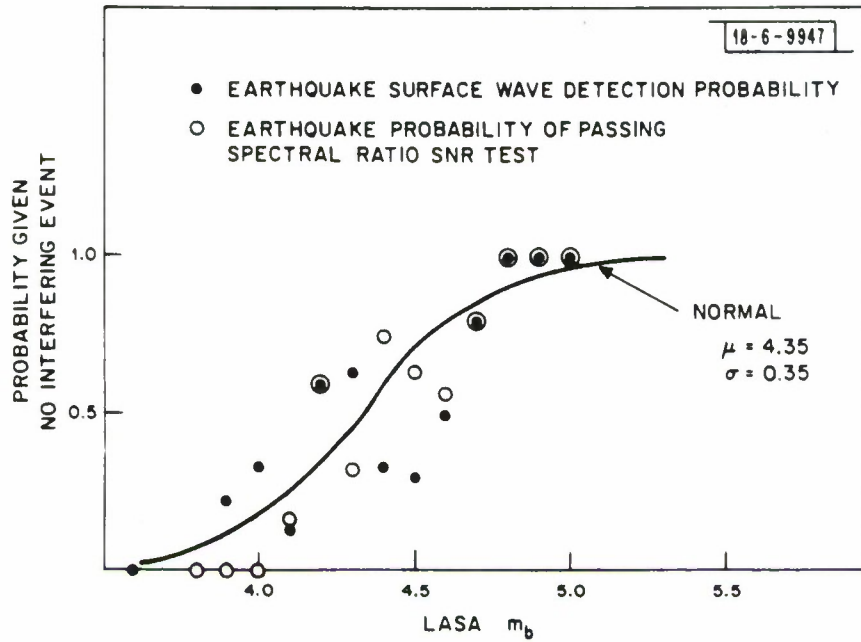


Fig. 3. Probability that $M_S - m_b$ or MSR can be applied to earthquakes with no interfering events.

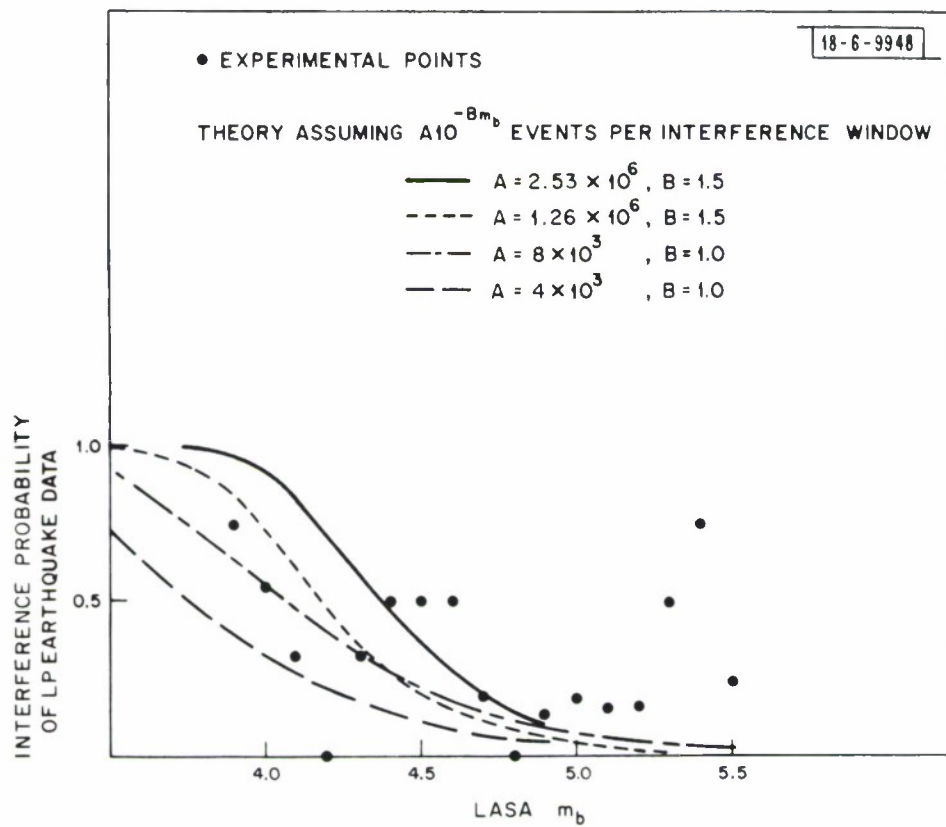


Fig. 4. Probability of interference of LP earthquake data.



Fig. 5a. Spectral ratio test results.

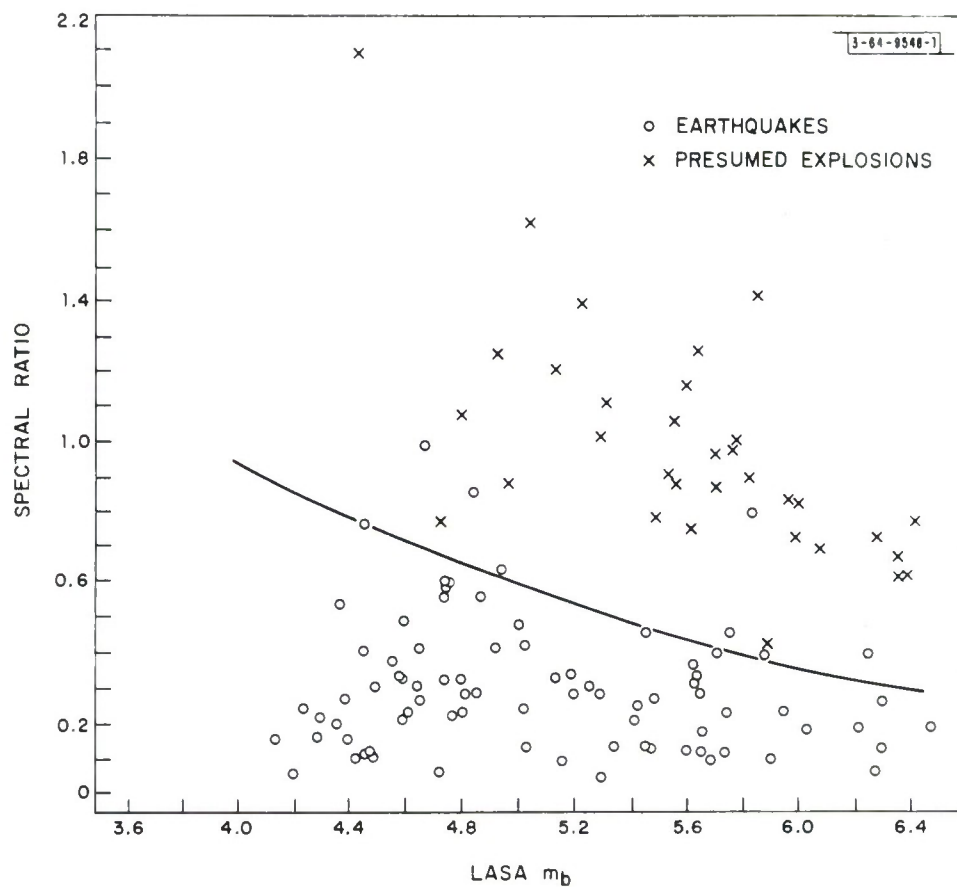


Fig. 5b. Modified spectral ratio test results.

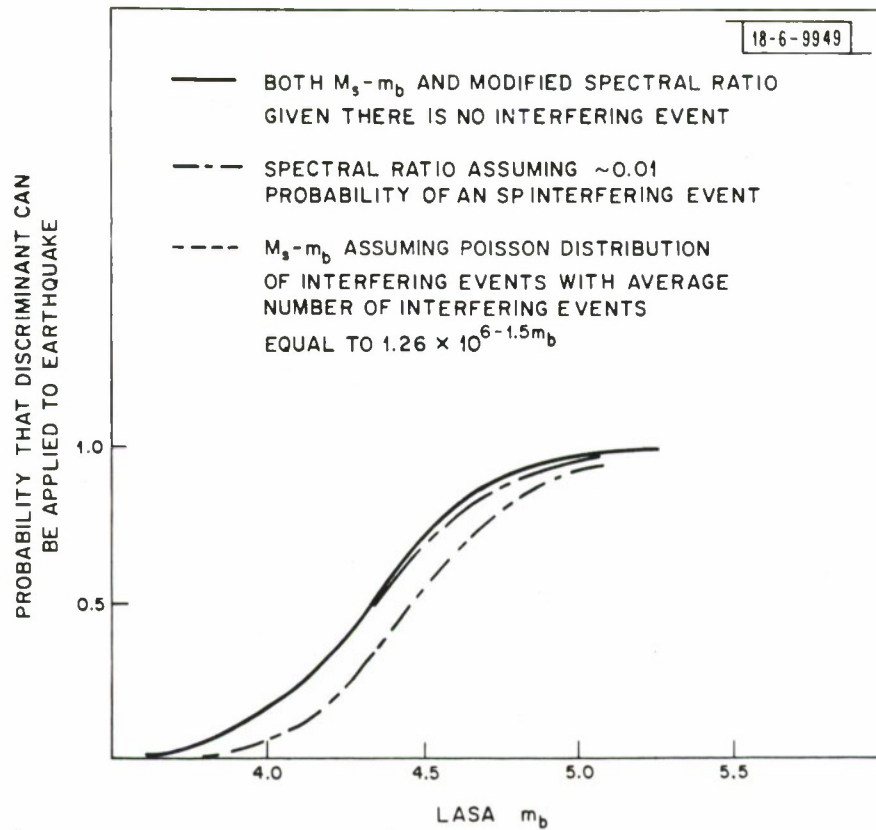


Fig. 6. Probability that discriminants can be applied to an earthquake.

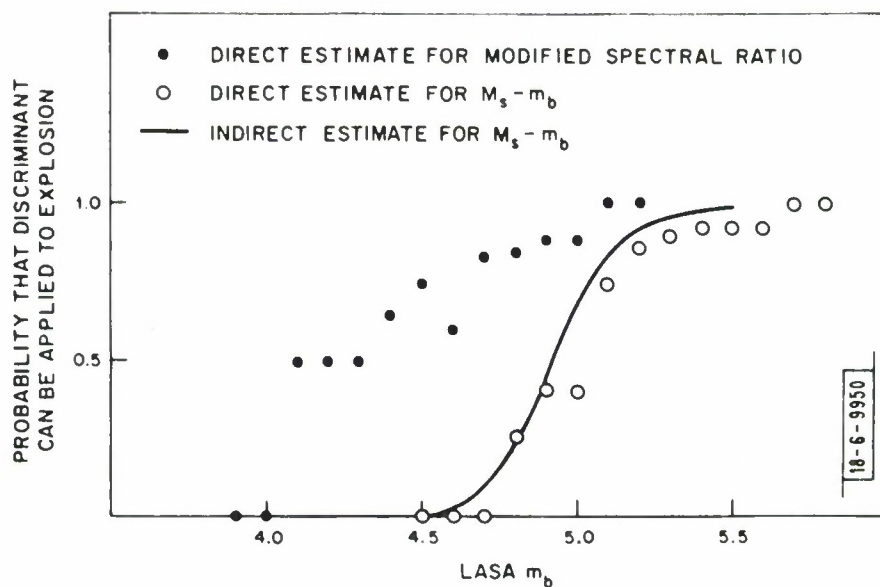


Fig. 7. Probability that discriminants can be applied to an explosion.

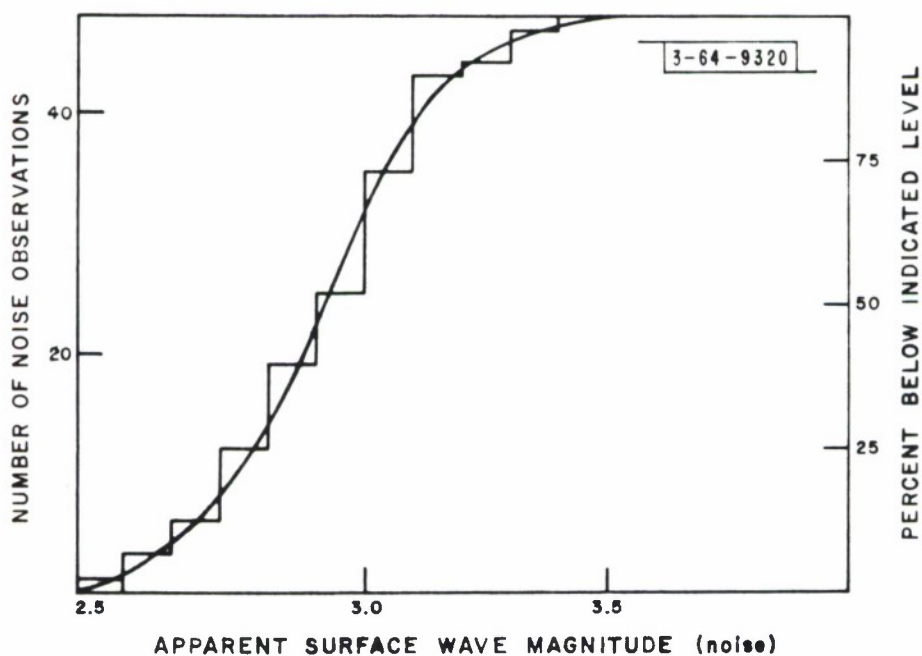


Fig. 8. Apparent surface wave magnitude of LP noise (Sino-Soviet locations assumed).

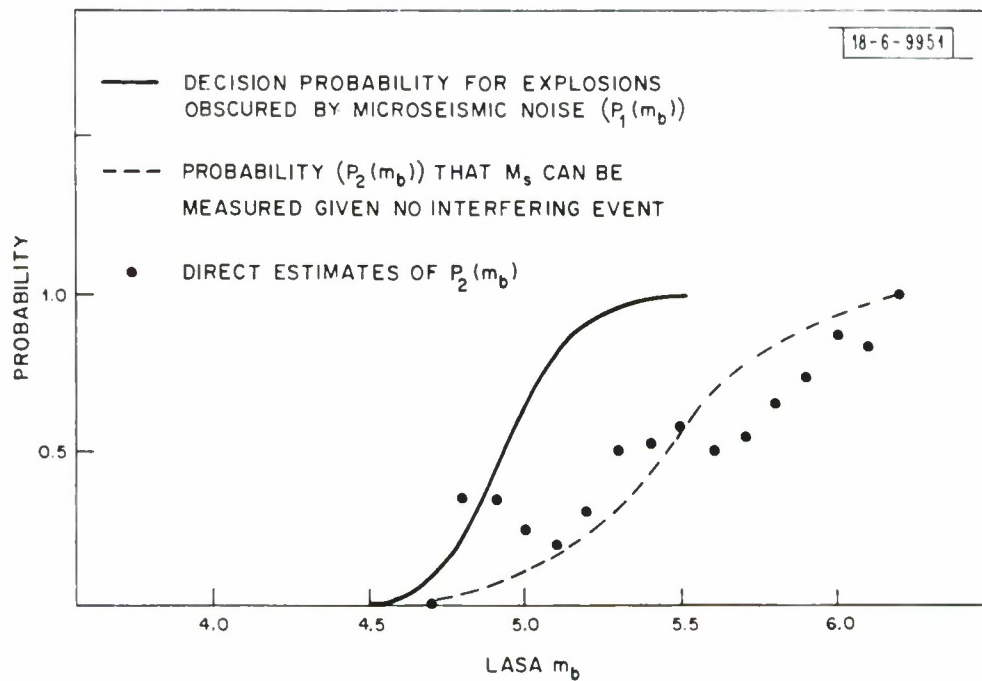


Fig. 9. Component probabilities for indirect estimate of probability that $M_S - m_b$ can be applied to an explosion.

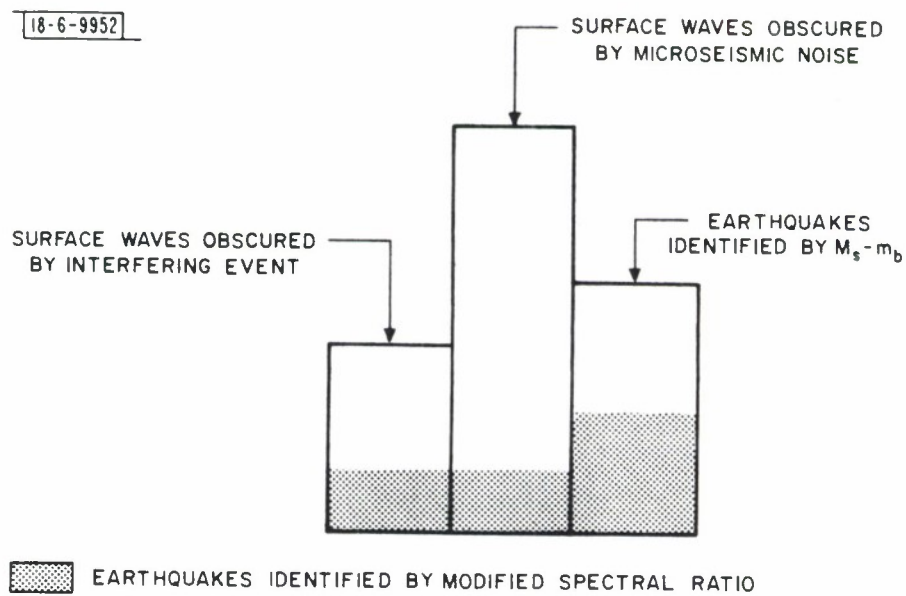


Fig. 10. Venn diagram indicating the independence of $M_S - m_b$ and MSR for earthquakes with $m_b \leq 4.5$.

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